"Lights-Out Operations for the Transition Region and Corona Explorer (TRACE) Using Operational and Architectural Approaches"

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Abstract

The National Aeronautics and Space Administration's (NASA) Small Explorer (SMEX) program provides frequent flight opportunities for highly focused and relatively inexpensive science missions. The Transition Region and Corona Explorer (TRACE), launched on April 1, 1998, is fourth in the series of SMEX missions, each managed and controlled from NASA's Goddard Space Flight Center (GSFC). Within the SMEX program, and throughout the agency, there has been a continuous push to lower costs from mission to mission. Ground data systems (GDS) providing telemetry processing and commanding have evolved throughout the SMEX program's lifetime, resulting in a TRACE GDS which enables lights-out operations and takes advantage of World Wide Web (WWW)-based architectures. As a result, the cost to prepare for TRACE launch and operations was reduced by more than 70% from the initial SMEX mission, and the projected cost for nominal operations was reduced by 50%.

The key architectural change that evolved during the SMEX program was the consolidation of command and control software used during the spacecraft integration and test phase with the command and control software used during the operations phase. This enhanced core system, known as the Integrated Test and Operations System (ITOS), has been augmented with additional operational components developed in other centers of expertise to form the complete TRACE GDS. Furthermore, the ITOS software has been ported to execute under a variety of operating systems, including Solaris, HPUX, and Windows NT. Java displays have been integrated to allow viewing from any computer via a WWW browser. An emergency response system based on Lotus Notes was also added to detect anomalies and alert operators.

Operationally, the goal was to reduce support from the original SMEX profile of three shifts, providing continual, 24-hour coverage, to a single shift, operating five days a week during normal business hours. To achieve these reductions, the Flight Operations Team (FOT) relies on the ground system for spacecraft monitoring during unattended passes at nights and on weekends.

This paper will discuss the experiences and philosophy for the TRACE ground system development and operations. Further, it will focus on the technology roadmap used by the SMEX program. Finally, the paper will examine future directions for the SMEX missions.

1. Introduction

Figures 1 and 2 show the success that was achieved in lowering both the costs of prelaunch preparation and development and annual routine operations. Although only the five SMEX missions are depicted, lessons learned from these missions have been and continue to be applied to other Goddard missions.

The Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) mission's GDS made significant strides towards lowering ground costs from prior GSFC missions such as the Gamma Ray Observatory (GRO) and the Upper Atmosphere Research Satellite (UARS). It was one of the first Goddard missions to transition from minicomputers to workstations, and made notable efforts to emphasize software reuse with other missions. In fact, the primary

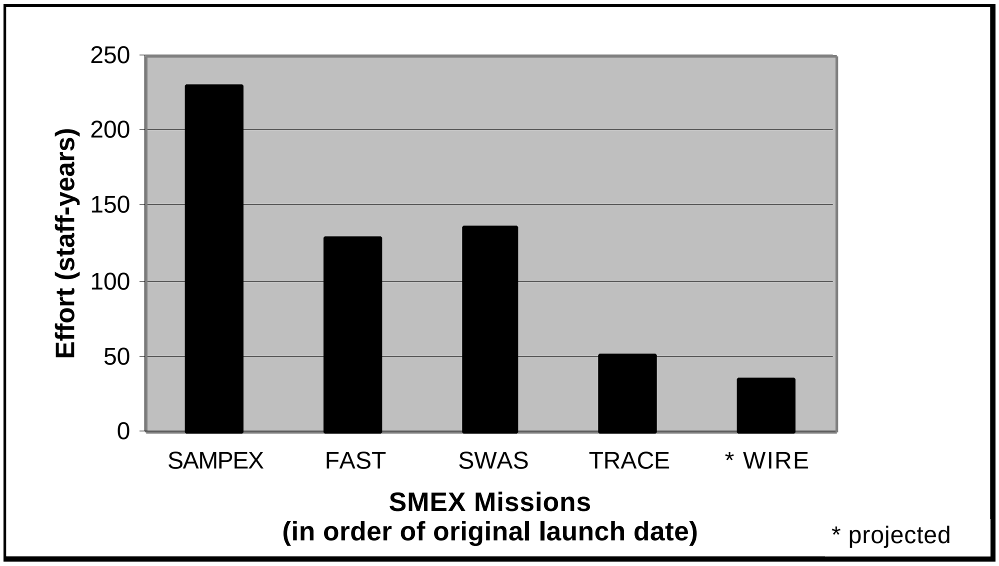

Figure 1. Ground System Prelaunch Cost[1]

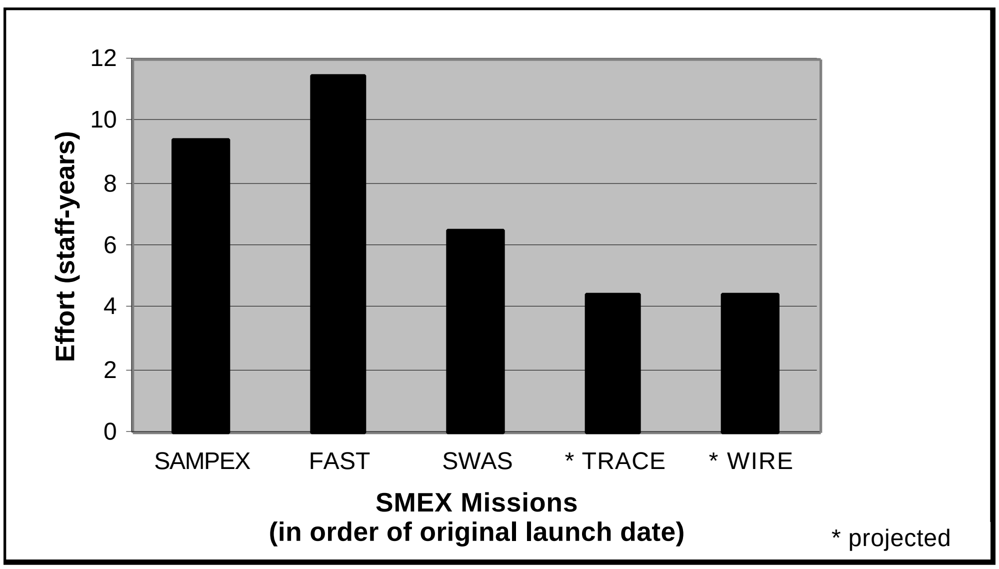

Figure 2. Annual Operations Cost[1]

focus of the first three SMEX missions prior to TRACE had been on *product-related* improvements such as software reuse. Although reuse among these GDS efforts had reached the 80% level, overall development cost had only been reduced by 40%. As a self-directed, continual improvement group, the TRACE team's emphasis on *process-related* improvement identified key process changes which resulted in even further cost savings. Development and operations philosophies focused on four key areas:

- Creating an Integrated Product Development Team (IPDT)
- Reducing the amount of traditional external testing and quality control

[1] Excludes network-related costs

- Streamlining of the procurement process
- Altering traditional operations concepts to take advantage of new technologies

However, an important first step undertaken by the SMEX team was the creation of a technology roadmap to highlight the opportunities and appropriate timeframes for these process changes to take effect.

2. Technology Roadmap

Figure 3 represents the SMEX technology roadmap, originally conceived in the Submillimeter Wave Astronomy Satellite (SWAS) mission timeframe and documented by the TRACE team. Early in its development cycle, the TRACE team realized that a potential target for lowering cost was to steer away from custom software as much as possible and to take advantage of emerging technologies, even if they conflicted with traditional operations concepts. This required some technology forecasting. In particular, a decision was made to evolve away from more costly high-end workstations and associated operating systems, and toward low-cost personal computers (PC). Additionally, there was an operational desire to use laptop computers for portability, though laptops at that time did not have adequate disk space or screen resolution to handle the needs of the FOT. However, the team anticipated the rate at which technology-related improvements would happen, and they trusted that the appropriate technology would soon be available to meet these desires. Technology improvements actually occurred much faster than anticipated. For example, the original FOT discussions indicated that a laptop with a minimum 1024 x 768 resolution and a two gigabyte (GB) hard disk would be required to meet their needs. Within two years of those early discussions, laptops with a 14.1” screen, 1280 x 1024 resolution, and four GB disks were readily available, and the TRACE team was prepared to rapidly take advantage of the hardware gains.

3. Integrated Product Development Team

The concept of an IPDT is not a new idea. However, the formation of the TRACE IPDT stressed joint development and partnering between previously independent development groups, breaking through traditional organizational barriers.

The TRACE IPDT served to streamline communications and lower developmental costs associated with communication-related products. A very significant portion of the cost to previous mission was spent on communication via thick, formal documents. Millions of dollars were spent generating, reviewing, and publishing these documents. The TRACE IPDT avoided these costs by removing the formal barriers that required the generation of the documentation and concentrating on personal interaction and the use of the Internet as a repository for information sharing. For example, Figure 4 shows the large savings that were accrued in the requirements gathering phase of the mission as compared to other previous missions. Agreements and requirements were easily documented on a central website, allowing for quick edits and distribution of changes, and eliminating the need for a multitude of review meetings. Additionally, the FOT had ready access to all documentation regardless of where a particular operational workstation or laptop was located.

An exceptionally important change for TRACE from the previous SMEX was the merging of the Integration and Test (I&T) system that was used for previous SMEX satellites with the independently developed mission operations system. In addition to the reduced software development costs, the new, combined ITOS system allowed display pages and procedures prepared by the FOT during the I&T phase to also be used during the operational phase, resulting in great time and cost efficiencies for the FOT. The next SMEX mission, the Wide Field Infrared Explorer (WIRE), will use the same system for the I&T and the operational phases, and the SWAS mission, which has had its launch delayed until 1999, will reengineer its GDS to use the same system.

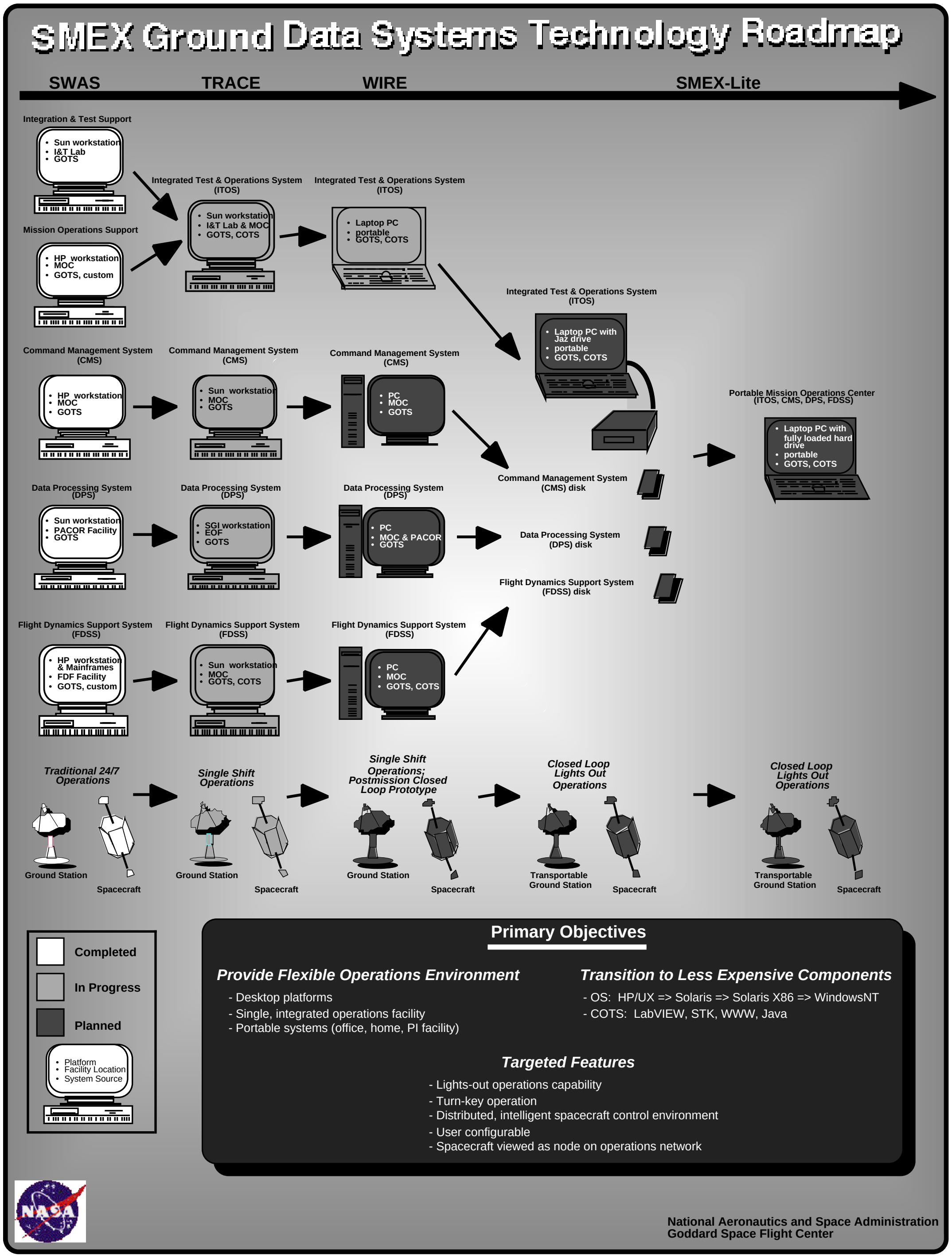

Figure 3. The SMEX Technology Roadmap

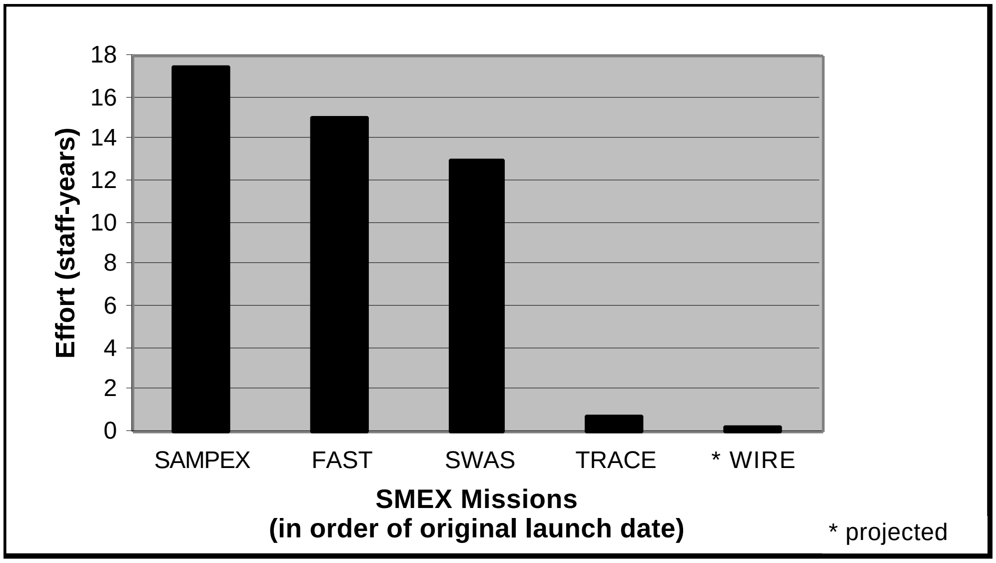

Figure 4. Ground System Requirements Gathering Cost

4. Streamlined Testing Approach

Efforts were also made to streamline the GDS testing. Testing approaches used on previous missions relied on multiple layers of independent testing which required much internal coordination and increased the overall testing costs. When analyzed, a significant amount of non-value added activity was identified which could be removed without diminishing the value of the overall testing effort. In particular, additional independent, external testing separate from the IPDT was eliminated whenever possible. For previous SMEX missions, a strong reliance on external quality control was used, but the team performing the testing and quality assurance often did not have a deep enough understanding of the operational concept to adequately evaluate the system. FOT members frequently commented that they had to repeat most tests and that they could often identify problems much quicker than their testing counterparts. One reason was that the FOT had access to the actual satellite and its associated data, whereas organizational and knowledge barriers frequently prevented the testers from similar access. Figure 5 shows the progression of testing efforts over the missions. For TRACE, the overall testing effort was reduced to one-sixth that for previous SMEX missions.

5. Streamlined Procurement Process

Another key process that was changed involved the procurement of hardware and software. On previous missions, procurement officers were assigned to track large computer purchases. The process was very cumbersome due to complex government regulations and the numerous interfaces required to monitor each purchase, which directly added to the time and cost for individual purchases. As a result, equipment would occasionally become outdated before it was finally delivered due to the long procurement process and the rapid pace of technology advancement. The TRACE team quickly embraced a new streamlined procurement process which permitted the use of a project-assigned government credit card. Use of the credit card allowed purchases to be made in hours and days instead of months and sometimes years. This flexibility also permitted the IPDT team to delay purchases as long as possible, allowing it to take advantage of lower hardware costs and continually improving technology.

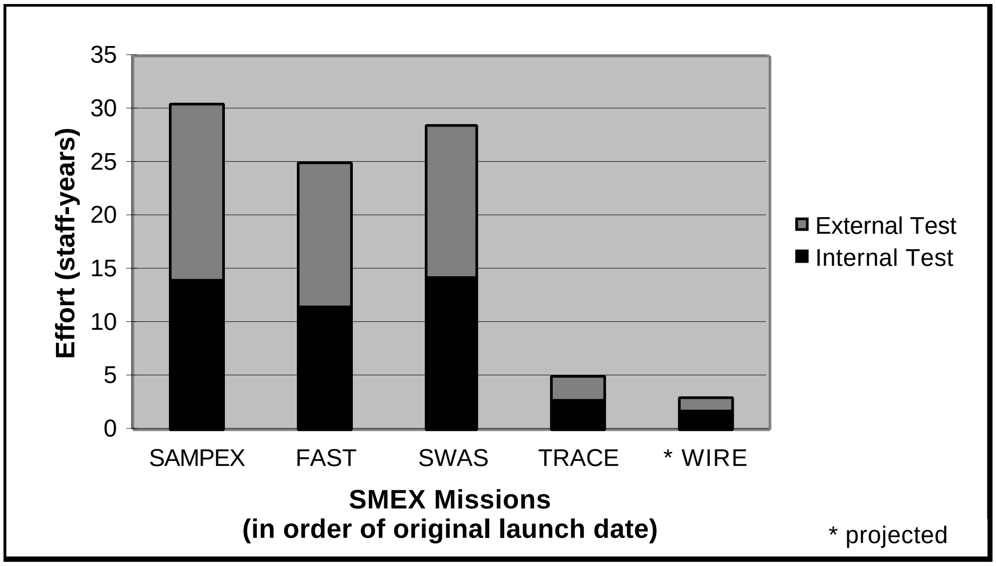

Figure 5. Ground System Testing Cost

6. New Operations Concepts

One of the most challenging tasks for the TRACE FOT has been to keep up with the rapid pace of technological improvements. On previous SMEX missions, improvements to the ground system typically came from FOT requests. The requests were evaluated by the ground system development team, who would assess the complexity and impact of the request, and if possible, schedule a time for its implementation. With the rapid advancement of distributed systems and networks technology, the FOT's operations concepts are now lagging behind the available improvements. Although new technology frequently has the potential to provide significant cost savings, it must still be integrated into a coherent operations profile.

With the transition to distributed systems and networks, the traditional Mission Operation Center (MOC) and resulting operations concepts have changed dramatically. For previous SMEX missions, the FOT only performed command and control functions in the MOC. Supporting activities, such as orbit determination, attitude analysis, and level-zero processing were supported through large institutional organizations and facilities. These institutional organizations were also responsible for supporting many other missions in addition to the SMEX missions. Complexity and cost of the hardware and software forced these functions to be housed separately.

With the migration of the institutional functions to workstations and PCs and the transportability associated with internet protocol (IP) based systems, the requirement for institutional facilities has largely been eliminated. For the TRACE launch, command and control, attitude determination, and command management functions were resident in the MOC, while science data level-zero processing occurred on a workstation located in an Experimenter Operations Facility down the hall from the MOC. After TRACE completes its one-month commissioning phase, the command and control functions will be migrated to the operations room used for the Fast Auroral Snapshot Explorer (FAST) satellite, allowing the WIRE spacecraft use of the MOC for its launch and early orbit (L&EO) activities. Similarly, after WIRE completes its commissioning phase, it will also be moved into the combined FAST and TRACE control center to make room for the SWAS launch.

There are no restrictions that require the control centers to be located at GSFC. In fact, SAMPEX operations have already migrated to Bowie State University for its extended mission operations phase. Extended mission and even nominal mission operations can be conducted in an office at a scientist's university as easily as from a control center located at GSFC. The flexibility exists for either scenario.

Transportability has also lessened the requirement for dedicated L&EO facilities. During this very dynamic phase of a mission, additional engineering support is required to help with emergencies. For TRACE, the L&EO Support Room was simply a room adjacent to the TRACE MOC, equipped entirely with PCs. The L&EO PCs have been made available for a variety of other functions following the required launch support. During some of the early TRACE launch simulations, FOT laptop computers were integrated into the L&EO Support Room. Following the simulations, these laptops were also used for other purposes. As with the MOC, the L&EO Support Room has become a "virtual support room", no longer requiring a fixed, single-purpose facility.

Just as hardware and software can be easily relocated today, functions can also. A common FOT mission support task is to trend data for analysis by an off-line group of engineers. The engineering support team typically provides the FOT with a list of parameters to trend, from which the FOT builds the necessary reports and delivers them to the support team. However, this package of trended data is typically a larger set of data than is required for the FOT's monitoring of the spacecraft health and safety.

The TRACE project viewed the generation of trending reports as an extraneous task being performed by the FOT. To support the TRACE mission, each engineering sub-group defined a set of parameters to be subsetted automatically by the ground system during standard post-pass processing. This data is then stored on open network data servers, allowing the engineering team direct access to their data as needed. The FOT is no longer required to serve as a "middle-man" in providing data to external parties. Through the use of distributed systems, entire processes are being eliminated.

7. Anomaly Resolution

Anomaly resolution provides an excellent example of how the various improvements have been tied together into an effective operations concept for TRACE. During the evening hours and on weekends, all passes are taken autonomously. Onboard commands automatically turn on the satellite's transmitter when the spacecraft is in range of the designated ground station. The satellite transmits the data to the ground and then turns off the transmitter at the end of the pass. TRACE passes usually are less than ten minutes in duration. The ground system has been designed to automatically monitor the telemetry stream for satellite limit violations or unexpected event messages from the ground system or satellite. If an anomaly is detected, the ground system forwards a message to an on-call FOT member's pager. The message lists any anomalous telemetry mnemonics along with their values. The FOT engineer can then download the last set of pass data to a laptop computer, which is configured with the ITOS software. The pass can be replayed, allowing the engineer to discern whether the problem is serious enough to warrant further onsite analysis in the MOC, or if the resolution can wait until the scheduled morning shift. By employing this capability, the engineer can immediately study the situation, and if necessary, schedule an emergency pass with a ground station to begin recovery procedures at the next available opportunity. Delays in recovery no longer are measured in hours due to staffing limitations, but are driven by the next available view period with a ground station.

8. Future Advances

The final SMEX mission is WIRE, currently scheduled to launch in September 1998. The WIRE ground system will rely on PCs for its MOC configuration instead of more costly UNIX workstations, providing further cost reductions in hardware procurement and maintenance.

Additionally, the WIRE operational requirements state that command loads be sent to the spacecraft during unattended hours. On TRACE, only one command load per day is required, and it can be easily scheduled during normal business hours. Since personnel are already working in the same room supporting the FAST satellite, there is no extra cost for that team to support a TRACE pass and uplink the command load to the satellite. Since WIRE will require both a daytime command load and a nighttime command load, additional staff would be required to uplink the nighttime command load. WIRE will also require that command loads be sent to the spacecraft on weekends as well as weekdays,, whereas TRACE and FAST mission profiles allow the FOT to transmit weekend command loads on Friday.

To alleviate WIRE's need for night and weekend staff, scripts will be developed which allow autonomous command loads to be sent to the spacecraft during unattended hours. Because they share a common ground system, autonomous commanding will first be tested on TRACE, while operations personnel are present in the MOC in a shadow mode. The WIRE team will then have the capability to perform both unattended telemetry monitoring and command load uplink. It is conceivable for future SMEX missions, or current missions in their extended mission phase, to have total lights-out operations for all passes. Off-line functions (e.g., mission planning, trending) will still be required, but the need to be physically present in the MOC for spacecraft passes will be eliminated.

Although ITOS was developed for the SMEX program, other GSFC projects, including the NEXUS pathfinder mission for the Next Generation Space Telescope, are evaluating the potential use of ITOS because of its portability and low-cost. Further cost saving measures will be evaluated during the WIRE mission next year. Because it uses a cryogenic cooler, the WIRE spacecraft will only have a scientific lifetime of four to eight months. After this period, the WIRE spacecraft will be available as an engineering test bed. Proposals considered for WIRE's extended mission include the use of magnetometers for onboard orbit determination and newer Consultative Committee for Space Data Systems (CCSDS) protocols for file-to-file transfers. The WIRE spacecraft and ground system will provide interested parties with an excellent opportunity to prove concepts on an active satellite.

9. Summary

The TRACE team has taken advantage of new capabilities in hardware, software, and network technology to develop an operations concept which results in dramatically lower mission costs and less risk to the satellite. The use of a closely coupled, empowered, and self-directed IPDT allowed for development of a significantly less-costly GDS. The operational concepts resulting from these new approaches and capabilities continue to evolve as new techniques are developed and evaluated. By taking full advantage of the hardware, software, and operational improvements, the SMEX program is moving forward to complete lights-out operations while still minimizing risk to its satellites.